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Spin susceptibility in the superconducting state of cuprates

T. Mayer [a], M. Eremin [a,b], I. Eremin [b,c], P.F. Meier [a,*]

[a] Physics Institute, University of Zurich, Winterhurerstrasse 190, CH-8057 Zurich, Switzerland
[b] Kazan State University, Kazan 420008, Russia
[c] Institute for Theoretical Physics, Freie Universitaet Berlin, D-14195 Berlin, Germany

Abstract

An analytic expression for the spin susceptibility in the superconducting state is derived taking into account strong correlation effects and the temperature dependence of the transverse nuclear spin–spin relaxation rates is calculated for both s- and d-wave pairing symmetries.

Keywords: Spin susceptibility; Strong correlations; Superconductivity; Singlet band

Up to now calculations of the spin susceptibility for layered cuprates were performed in the frame of weak-coupling approximations. It is known, however, that cuprates belong to Mott–Hubbard doped materials where electron correlation effects are very important. Therefore investigations of the influence of these correlation effects on the spin susceptibility are very topical. For the normal state, correlation effects have been studied by Hubbard and Jain [1] and by one of us [2]. In this work we report the analytic expression for the spin susceptibility below T_C which results for a particular model system that is closely related to models based on the idea of the formation of copper–oxygen singlets in layered cuprates [3,4].

The starting point is the Hamiltonian

$$H_\psi = \sum t_k \psi_k^{pd,\sigma} \psi_k^{\sigma,pd} + \frac{1}{2}\sum J_{ij}\left[(S_i S_j) - \frac{n_i n_j}{4}\right] + \frac{1}{2}\sum G_{ij}\delta_i\delta_j - \sum h_i S_i$$

where the bare kinetic energy

$$t_k = 2t_1(\cos k_x + \cos k_y) + 4t_2 \cos k_x \cos k_y + 2t_3(\cos 2k_x + \cos 2k_y) + \cdots$$

accounts for hopping between nearest (t_1) and further neighbors. J_{ij} is the superexchange coupling parameter of copper spins, G_{ij} is the Coulomb repulsion between doped holes δ_i and $n_i = 1 - \delta_i$. The last term takes into account an external magnetic field. The $\psi_k^{pd,\sigma}(\psi_k^{\sigma,pd})$ are composite copper–oxygen creation (annihilation) operators of copper–oxygen singlet states in the plane. We emphasize that, in contrast to conventional weak-coupling approaches, the anticommutator $\psi_i^{pd,\uparrow}\psi_i^{\uparrow,pd} + \psi_i^{\uparrow,pd}\psi_i^{pd,\uparrow} = P + \langle s_i^z\rangle$ depends on the doping level δ_i and magnetization $\langle s_z\rangle$. A more detailed discussion of this aspect can be found in Ref. [4]. Here we just note that the quantity P is about $(1+\delta)/2$ near optimal doping. Since the commutator algebra is different from that valid in the weak-coupling conventional Fermi liquid scenario, the general expression for the susceptibility is quite different from the standard Pauli–Lindhard formula. It is given by

$$\chi(\omega, q) = \frac{\chi_0(\omega, q)}{\frac{J_q}{2}\chi_0(\omega, q) + \Pi_1(\omega, q)} \quad (1)$$

where

* Corresponding author. Tel.: +41-1-6354016; fax: +41-1-6355704.
E-mail address: pfmeier@physik.unizh.ch (P.F. Meier).

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